

Preface

The years 2006 and 2007 mark a dramatic change of peoples view regarding climate change and energy consumption. The new IPCC report makes clear that humankind plays a dominant role on climate change due to CO₂ emissions from energy consumption, and that a significant reduction in CO₂ emissions is necessary within decades. At the same time, the supply of fossil energy sources like coal, oil, and natural gas becomes less reliable. In spring 2008, the oil price rose beyond 100 \$/barrel for the first time in history. It is commonly accepted today that we have to reduce the use of fossil fuels to cut down the dependency on the supply countries and to reduce CO₂ emissions. The use of renewable energy sources and increased energy efficiency are the main strategies to achieve this goal. In both strategies, heat and cold storage will play an important role.

People use energy in different forms, as heat, as mechanical energy, and as light. With the discovery of fire, humankind was the first time able to supply heat and light when needed. About 2000 years ago, the Romans started to use ceramic tiles to store heat in under floor heating systems. Even when the fire was out, the room stayed warm. Since ancient times, people also know how to cool food with ice as cold storage. Nevertheless, for most of our history, heat and cold storage did not play a significant role for most people in every day life. This has changed during the time of the industrial revolution when the demand for comfort in domestic buildings increased. Today, refrigerators, space heating, and domestic hot water are a part of every household. Thermal energy storage (TES), which is heat and cold storage, plays an important role in many energy systems, not only house holds but also industrial processes. Even though storage itself will never save energy, it is often able to improve a system in a way that it is more energy or cost efficient. The advantage of using heat storage is that it can match supply and demand when they are not at the same time, and second, that a storage can match different powers on demand and supply side. The energy used can have different sources, which are renewable and non-renewable. Especially solar energy is not continuous and thus heat storage is necessary to supply heat reliably. When solar collectors are used to heat domestic hot water, the storage also matches the different powers of the solar collector field, which collects the energy over many hours of the day, to meet the demand of a hot bath that is filled in only several minutes.

The best-known method of thermal energy storage is by changing the temperature of a storage material. Because we can feel the temperature change by our senses, we call this method sensible heat storage. Sensible heat storage is used for example in hot water heat storages or in the floor structure in under floor heating. An alternative method is changing the phase of a material. The best-known examples are ice and snow storage. Their phase change from solid to liquid hereby is especially advantageous, as the melting and solidification occur at a constant temperature, the melting temperature. The storage materials are called phase change materials, or short PCM. Because of the temperature being constant, the heat

storage cannot be felt and is called latent heat storage, or short LHS. Due to the constant melting temperature, latent heat storage also allows the stabilization of the temperature. An example is the cooling of drinks using ice. Further on, latent heat storage is also a method of heat storage with a high storage density compared to sensible heat storage when the temperature change in an application is small.

The use of latent heat storage in form of huge ice storages for cooling applications in industry and for space cooling in large buildings is widespread today. Since the oil crisis in the early 1970s other materials than ice with a large range of melting temperatures have been investigated, mainly for solar heating applications. Today, a high variety of storage materials and many products for different applications are available and well established on the market. Examples are the temperature stabilization in transport containers, in peoples clothing, and in buildings. In several other applications, e.g. industrial applications and power generation, the perspectives are improving because of the development in the energy market and new national and international policies.

At this state of the technology of latent heat storage, there is intensive R&D on many aspects as indicated by an increasing number of R&D projects and publications in scientific journals. There were several activities specialized on latent heat storage within the Implementing Agreement (IA) for Energy Conservation through Energy Storage (ECES) of the International Energy Agency (IEA), like IEA Annex 10 "Phase Change materials and Chemical Reactions for Thermal Energy Storage" and Annex 17 "Advanced Thermal Energy Storage Techniques - Feasibility Studies and Demonstration Projects" that finished in 2006. Ongoing or recently started activities are Annex 14 and Annex 20, and Task 32 of the Solar Heating and Cooling program. There are regularly organized conferences where sessions on latent heat storage are included. Examples are the thermal energy storage conferences (called STOCK conferences) organized by the ECES IA of IEA, the last ones being FUTURESTOCK (2003) and ECOSTOCK (2006), and others like EUROSUN (2002 and 2006). A conference dealing with heat transfer fluids with enhanced thermal storage capacity is also organized regularly, the last one being the "7th Conference on Phase Change Materials and Slurries for Refrigeration and Air Conditioning" (2006).

Despite the interest in the technology of PCM by scientists and engineers working in R&D, in industry, at universities, and at institutes, indicated by the large number of publications in journals and presentations at conferences, there is no single source available that can serve as an "introduction into basics and applications". The only book available specialized on latent heat storage was written some 20 years ago by G.A. Lane and has two volumes. The titles are "Solar Heat Storage: Latent Heat Material - Volume I: Background and Scientific Principles" published in 1983 and "Solar Heat Storage: Latent Heat Material - Volume II: Technology" published in 1986. In some aspects, this book is very detailed and not really an introduction, in many other aspects the technology has advanced significantly so that the description in the book is out of date. For example, today companies have taken over the production of PCM and available technologies for

their encapsulation have dramatically changed due to the development in plastics in the past decades. In addition, heat transfer, storage concepts, and application examples are not described thoroughly. Further on, the book is out of print. Recently a new book with the title “Thermal energy storage - Systems and applications” written by I. Dinçer and M.A. Rosen was published. It covers many fields of thermal energy storage like sensible heat storage and exergetic analysis. It is however research oriented and written for advanced students in engineering and practicing engineers. Further on, the part on applications of latent heat storages is restricted to industrial applications, mainly using ice storage. Another recent publication is “Thermal energy storage for sustainable energy consumption – fundamentals, case studies and design” published within the NATO Science series II. Mathematics, Physics and Chemistry. It includes several chapters on the technology and applications of latent heat storage written by the authors of this book. These chapters are based on lectures given within a summer school sponsored by the NATO titled “Advanced Study Institute on Thermal Energy Storage for Sustainable Energy Consumption (TESSEC); Fundamentals - Case Studies - Design”. The book covers many technologies for heat and cold storage, and consequently the parts on latent heat storage are only a very brief introduction. Therefore, we decided to write this book as an introduction into basics and applications on heat and cold storage with PCM for researchers and for graduate and PhD students in the fields of science and engineering. The chapter on heating and cooling in buildings can also serve architects as an introduction into the new possibilities given by the application of LHS.

The scope of this book is to summarize and explain the most important basics and applications in a single text. To make the book a readable introduction, we tried to keep the length in the range of 300 pages. This means it cannot be a complete coverage or review of PCM technology; the focus is on the explanation of general concepts and their discussion on selected examples. To go beyond an introduction, each chapter supplies many references with focus on such references that serve as an introduction into a special aspect, interesting websites, and other similar information.

As an introductory text, we tried to write the book in a way that things can be understood at the level of a graduate student of science or engineering. Due to the phase change, latent heat storage is considerably more complex than sensible heat storage and the understanding of many technical aspects requires long experience. Therefore, in some cases things have been simplified to allow the reader to understand general concepts. Further on, the book contains many derivations of basic equations, examples, graphs, and tables. To make reading easier, the appendix also includes a list of the most important definitions.

The selection of the material and its order is crucial for an introductory text. This book is based on the experience of several years of presentations and publications for scientists and for non-scientists. Nevertheless, the selection of the material and its order within this book has been reworked many times to give it a logical structure and make it not just a compilation of material. Additionally, the

nomenclature used in the past was changed where necessary to be consistent throughout the whole book.

The discussion in this book follows the order from materials to components, then to systems, and finally to applications. The book covers the following topics, each in a single chapter:

1. Basic thermodynamics of thermal energy storage
2. Solid-liquid phase change materials
3. Determination of physical and technical properties
4. Heat transfer basics
5. Design of latent heat storages
6. Integration of active storages into systems
7. Applications in transport and storage containers
8. Applications for the human body
9. Applications for heating and cooling in buildings

Applications in industry and power generation are currently in their first stage, besides ice storage, which is already treated in other books. These applications are therefore not included here. Considerable space has been devoted to measurement of properties. This topic becomes more and more important with increasing commercialization of PCM and until now has often been done without sufficient accuracy.

I hope that this book is helpful to all its readers. In any case, any kind of feedback is appreciated.

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Heat and cold storage with PCM

An up to date introduction into basics and applications

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